

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION  
International Bureau



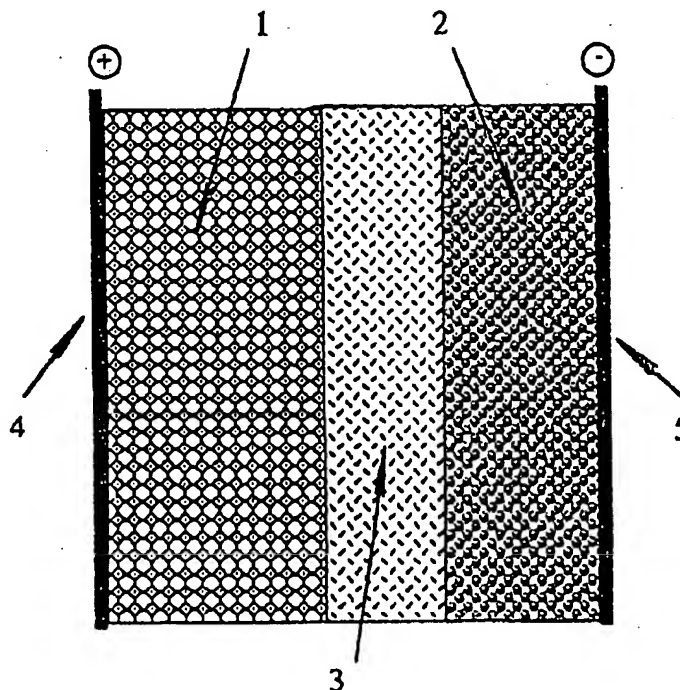
INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> : <b>H01M 10/40, 4/48, 4/58</b>		A1	(11) International Publication Number: <b>WO 99/59218</b>
			(43) International Publication Date: 18 November 1999 (18.11.99)
(21) International Application Number: PCT/EP99/03261		(81) Designated States: CN, JP, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).	
(22) International Filing Date: 8 May 1999 (08.05.99)			
(30) Priority Data: 98810431.1 12 May 1998 (12.05.98) EP		Published <i>With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i>	
(71) Applicant (for all designated States except US): ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE (EPFL) SRI [CH/CH]; CH-1015 Lausanne (CH).			
(72) Inventors; and			
(75) Inventors/Applicants (for US only): GRÄTZEL, Michael [CH/CH]; Chemin du Marquisat 7a, CH-1025 St. Sulpice (CH). SUGNAUX, François, R. [CH/CH]; Chemin du Taux 9, CH-1807 Blonay (CH). PAPPAS, Nicholas [CH/CH]; Chemin de Veilloud 10, CH-1014 Ecublens (CH).			
(74) Agent: HAMMER, Bruno; Sunneraiweg 21, CH-8610 Uster (CH).			

(54) Title: PRIMARY OR SECONDARY ELECTROCHEMICAL GENERATOR

(57) Abstract

A high power density and high capacity primary or secondary electrochemical generator in which at least one electrode (1,2) is composed of an electrically active solid material, said electrode having a mesoporous texture forming a bicontinuous junction of large specific surface area with the electrolyte. The specific morphology of the electro-active material permits high rates of ion insertion in the solid while allowing for rapid ion transport in electrolyte present in the porous space of the electrode. Specific methods for preparation of said electrode are disclosed, in particular the control of the electrode morphology by use of surfactant assemblies such as surfactant micelles exerting a templating effect during the chemical synthesis of said electro-active material.



BEST AVAILABLE COPY

**FOR THE PURPOSES OF INFORMATION ONLY**

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakhstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		
EE	Estonia						

5

## PRIMARY OR SECONDARY ELECTROCHEMICAL GENERATOR

---

### 10 FIELD OF THE INVENTION

The invention relates to a high power density primary or secondary generator and, more specifically a generator in which at least one electrode is composed of a solid material characterized by a mesoscopic morphology. An electrolyte is  
15 present in the mesoporous network of said electrode forming a bicontinuous junction of very large surface area with the electroactive solid.

The invention also relates to an electrode of this type having a large ion exchange capacity and high electric power density that makes it particularly  
20 suited for application as a cathode or anode in a primary or secondary electrochemical generator, such as a lithium ion battery.

The invention also relates to processes for obtaining an electrode of this type involving sol gel precipitation and subsequent baking of the electrically active  
25 solid material. It discloses methods to produce the specific mesoporous morphology of the electrode, required for optimal performance of the electrochemical generator. More specifically, it discloses the use of surfactant assemblies as templates to induce the desired electrode texture during the formation of the electro-active solid.

To enhance the performance of the electrochemical generator, in particular with respect to its energy density and power density, all its constituent elements, in particular the electrode materials, the current collector, as well as the separator and the composition of the electrolyte have been scrutinized to allow for the  
5 judicious selection of the optimal combination of said constituents. The physical configuration of the generator elements, notably the effect of electrode and spacer thickness and porosity as well as their conformation has been examined.

## 10 DESCRIPTION OF PRIOR ART

European patent application EP 0 709 906 A1 discloses a positive electrode composed of a sintered mass of lithium compound oxide, the mean particle size of the electrically active powder being 33  $\mu$ m. The particles are pressed into pellets of 1.5 mm size by applying high pressure with simultaneous baking  
15 at 350 to 700 °C. They report an improvement in the resistivity when baking at the elevated temperature presumably due to a degree of sintering within the active mass, thus improving somewhat the connectivity in the active material. U.S. Pat. No. 5,604,057 discloses a cathode comprising amorphous microporous, sub-micron-size, lithium intercalateable manganese oxide having  
20 an internal surface area greater than about 100 m<sup>2</sup>/g. Electrodes are fabricated by mixing the oxide with a binder, containing optionally a conducting polymer and heating the composite material at a temperature up to 400 °C. The temperature is limited to this value to prevent crystallization of manganese oxide. The high surface area and the amorphous nature of the active material  
25 structure proposed seem to increase the initial capacity of fabricated electrodes but the connectivity is hindered. Interior connectivity of the particles is poor and therefore requires a binder and/or a conducting binder within the electrode fabrication mixture. Another drawback in electrode construction with the amorphous material is that the exposure to temperatures can alter its structure  
30 by crystallization, limiting the reported benefits arising from its amorphous structure.

U.S. Pat.No. 5,211,933 and 5,674,644 disclose a method for the low temperature preparation of the spinel  $\text{LiMn}_2\text{O}_4$  and layered  $\text{LiCoO}_2$  phases prepared at temperatures less than  $400^\circ\text{C}$  using acetate precursors. The  $\text{LiMn}_2\text{O}_4$  powder obtained comprises grains or crystallites ranging in size  
5 between  $0.3\ \mu\text{m}$  and  $1\ \mu\text{m}$ . Pellets are pressed containing this powder and about 10% carbon black and used as positive electrodes in lithium ion batteries. The particle sizes claimed are large to suit high rate discharge electrodes and connectivity within the active material particles is not ensured by special bonding, the conductivity enhanced by mixing in carbon powder to the active  
10 powder.

U.S. Pat. No. 5,700,442 discloses insertion compounds based on manganese oxide usable as positive electrode active material in a lithium battery, prepared by reacting  $\gamma\text{-MnO}_2$  powder with a lithium compound at  $150$  to  $500^\circ\text{C}$  for an adequate time to convert these solid precursors to a spinel type. The specific  
15 surface of the resulting powder is below  $7\ \text{m}^2/\text{g}$ . The large particle sizes, as deduced from the low specific surface area claimed here are not suited for high rate discharge electrodes.

European patent application EP 0 814 524 A1 discloses a spinel-type lithium manganese complex oxide for a cathode active material of a lithium ion  
20 secondary battery. The average particle diameter is between  $1$  and  $5\ \mu\text{m}$  and the specific surface area between  $2$  and  $10\ \text{m}^2/\text{g}$ . The large particle sizes, thus the low specific surface areas claimed here, are not optimum for high rate discharge electrodes.

25

#### BRIEF SUMMARY OF THE INVENTION

As compared to these known features of the prior art, the invention provides and electrochemical generator in which at least one electrode consists of a  
30 mesoscopic, bicontinuous structure, composed of an interconnected solid material and of an interconnected network of mesopores. The electrically active solid is employed as a host for accommodating ions by an insertion process. At the same time, it serves to sustain the flow of electric current during charging

and discharging of the battery. Said electrically active solid is in contact with an interconnected porous space filled with electrolyte, the latter serving for ionic transport. Said electrode is characterized by the presence of an extremely large interface between the solid and the electrolyte, comprised between 10 and

5 3000 m<sup>2</sup>/g electrode material, permitting rapid exchange of ions between the solid and liquid phase. The architecture of the solid phase is designed to overcome the impediment of ionic diffusion in the electrolyte encountered with conventional high surface area electrodes. The specific three dimensional structure of the electrode disclosed by the invention ascertains interconnectivity

10 and mechanical stability of the solid phase providing ease of access of the electrolyte to the entire pore space. Furthermore, it renders possible the conduction of electric current within the solid even in the absence of conductive binders which are mixed with the electrically active material in conventional batteries to enhance electronic conductivity of the electrode. The electrically

15 active material in the form of such a mesoscopic morphology is obtained, for example, by employing surfactant assemblies exerting a templating effect during the formation of the solid from water-soluble precursor compounds or by sol-gel synthesis of a xerogel and subsequent sintering under appropriate conditions.

20

#### BRIEF DESCRIPTION OF THE INVENTION

Electrodes of lithium manganate, LiMn<sub>2</sub>O<sub>4</sub> serving as cathode in the electrochemical generator are prepared by casting an aqueous mixture of the manganate precursor by the doctor blading technique or by screen printing or

25 dip coating of the substrate. The gel precursor is precipitated starting from homogeneous solutions of manganous diacetate or manganous diacetylacetonate at 0.13 M and LiOH at 1.3 M. The [Li]/[Mn<sup>3+</sup>] ratio equals to 10 for each precipitation reaction. The reaction temperature is fixed at 110°C and the pH of the reactants is increased to basic values (~12-13) using the

30 concentrated LiOH solution. In each experiment, the manganous salt solution and the LiOH solution are separately dissolved, before mixing them in a batch reactor with agitation. The reaction time is 2 hours after which the hydrolytic

reaction between LiOH and the manganate salt is terminated by rapidly cooling the solution to less than 10°C in an ice bath.

The gel is applied in concentrated form to the substrate. Its consistency is controlled by the proportion of water in the mixture and the effectiveness of ambient drying of the cast layer. Each layer provides 0-3 microns of the dry precursor in porous form. This process is repeated to build up layers of many microns. After deposition of the precursor, the film is heated at 700-750 °C in air with a temperature gradient of 5-10 °C/min. and few minutes rest at peak temperature. **Figure 2** present the morphology of the electrode obtained by scanning electron microscopy.

An electrode of this type having in its composition an electroactive material in the form of a mesoscopic morphology provides a high energy storage capacity and high power density and may be used in both primary and secondary electrochemical generators. The electrolyte used in such a generator is preferably one containing protons or lithium ions. Other alkali or alkaline earth metals may also be used. According to a preferred embodiment, the electrolyte contains lithium ions brought into the form of one of its salts such as tetrafluoroborate, hexafluorophosphate, hexafluoroantimonate, hexafluoroarsenate, trifluoromethane sulfonate, bis (trifluorosulfonyl) imide, tris (trifluorosulfonyl) methide, trifluoromethanesulfonate, trifluoroacetate, tertachloroaluminate or perfluorobutane sulfonate. According to the preferred embodiment, the solvent of the electrolyte is an aprotic solvent or a liquid salt, such as ethylene carbonate, propylene carbonate, dimethylcarbonate, diethylcarbonate, dioxolane, butyrolactone, methoxypropionitrile, methoxyethoxy propionitrile, methoxy-diethoxypropionitrile, methoxyacetonitrile, tetrafluoro-propanol or mixtures of these solvents. Another preferred embodiment of the invention uses a molten salt as a solvent for the lithium ion containing salt, such as methyl-ethyl-imidazolium trifluoromethanesulfonate or methy-ethyl-imidazolium bis (trifluorosulfonyl) imide and corresponding dimethyl-ethyl-imidazolium salts with the above anions. The material used for at least one electrode in form of a mesoporous layer may be an electrically active material, but according to the preferred embodiment, this material is chosen so as to form an insertion compound with alkali or alkaline earth metals, thereby

providing a secondary electrochemical generator. An electrically active material of this type will be chosen for example from the oxides or chalcogenides of transition metals or their lithiated or partially lithiated forms, such as  $\text{TiO}_2$ ,  $\text{Nb}_2\text{O}_5$ ,  $\text{WO}_3$ ,  $\text{MoO}_3$ ,  $\text{MnO}_2$ ,  $\text{Li}_y\text{Mn}_2\text{O}_4$ ,  $\text{HfO}_2$ ,  $\text{TiS}_2$ ,  $\text{TiSe}_2$ ,

- 5  $\text{Li}_y\text{NiO}_2$ ,  $\text{Li}_y\text{CoO}_2$ ,  $\text{Li}_y(\text{NiCo})\text{O}_2$ , or  $\text{Sn}_y\text{O}_2$ . According to the preferred embodiment of the invention, an electrode, which may be the cathode or the anode, depending on the electrical activity of the electrode used as the counterelectrode, is composed of mesoporous titanium dioxide in the form of anatase or in the form of a mixture of rutile and anatase. containing more than
- 10 50% anatase. In the presence of lithium ions, the titanium dioxide in mesoporous form is prone to form an intercalation compound  $\text{Li}_y\text{TiO}_2$  in which the intercalation coefficient has a high value between 0.6 and 0.8. For a cell in which  $x = 0.8$  and where the counterelectrode is made of lithium metal, the theoretical energy density is  $400 \text{ Wh kg}^{-1}$  assuming a mean value of the cell
- 15 voltage of 1.5 V. This high capacity is associated with a high value for the specific power, the later reaching values of  $2.3 \text{ kW/kg}$ . Results of this kind can not be obtained with the technologies of the prior art, such as described by W.J. Macklin et al. (Solid state Ionics 53 -56 (1992) 694-700) in which both the specific power and capacity of a conventional  $\text{TiO}_2$  electrode is significantly
- 20 lower.

- When an electrically active compound also capable of inserting lithium ions is used for the other electrode, the electrochemical generator of the invention is a secondary (rechargeable) generator of the "rocking chair" type, the principles of which was descibed for the first time by M. Armand (Materials for Advanced
- 25 Batteries, D.W. Murph et al. ed. Plenum press N.Y. 1980, p145). According to a preferred embodiment of the invention, the rocking chair configuration employs  $\text{TiO}_2$  in the anatase structure as anode material, while  $\text{Li}_y\text{Mn}_2\text{O}_4$  in amorphous or crystalline form is used for the cathode. The  $\text{Li}_y\text{Mn}_2\text{O}_4$  ( $y \approx 2$ ) material disclosed by the invention is also present in the form of a mesoporous
- 30 morphology, yielding cathodes of high capacity, i.e. close to the theoretical maximum of  $280 \text{ Ah kg}^{-1}$ . The overall capacity of such a  $\text{TiO}_2/\text{Li}_y\text{Mn}_2\text{O}_4$  rocking chair battery reaches up to  $140 \text{ Ah kg}^{-1}$ , the average cell voltage being



2 volts and the power density based on the material densities 2000 to 3000 W/kg. For such a  $\text{TiO}_2/\text{Li}_y\text{Mn}_2\text{O}_4$  rocking chair thin layer cell configuration power densities of 0.5 to 1.5  $\text{mW cm}^{-2}$   $\square\text{m}^{-1}$  are observed.

The mesoporous electrode structure of the said cell configuration and the  
5 battery device as a whole also provide for improved local heat dissipation or exchange from the solid during high rate discharge, thus protecting potentially sensitive (active) materials of the battery from degradation, as exposure to extreme temperatures is minimized.

$\square$ The mechanical strength is enhanced by controlled sintering process, as the  
10 interconnected loops and/or arches are created having a typical aspect ratio of ca. 4, complementing the contribution to the reduction of the system entropy resulting from the natural self-organizing by the templating effect, leading to a structural toughness and robustness of the mesoporous network that can therefore sustain the capillary forces, i.e. not breaking under the intense local  
15 pressure when the pores are filled with electrolyte, and most importantly, able to support the strain and mechanical stresses resulting from the volumetric expansion/contraction resulting from the  $\text{Li}^+$  insertion/extraction process during the rocking chair battery operation. The later effect induces improved structural integrity on cell cycling, which produces enhanced cyclability as capacity fading  
20 due to active material disintegration and discontinuity (decreased electrical connectivity and conductivity) is minimized. Consequently, better solid phase connectivity is ensured with the above mentioned smaller sized "particles" or "grains" or described elemental structural units comprising the mesoporous electrode.

25 The preparation according to the preferred embodiment of the invention, results in a crystalline phase that enhances the  $\text{Li}^+$  insertion kinetics as long crystalline rows are formed at high temperatures and at short times. The sintered metal oxide layer density (and pore or future anhydrous electrolyte mass vs. oxide mass ratio) can be controlled by solvent (e.g. water) dilution of the oxide  
30 precursor and the aggregation state (oxide mass vs. water) of the precursor solution applied.

The full connectivity of the mesoporous space combined with the low tortuosity enables a lower porosity (higher active mass to void (for electrolyte) ratio) to be more effective with respect to the electrolyte function i.e.  $\text{Li}^+$  diffusivity.

5 The two proposed mineral electrodes instead of carbon or lithium metal offer safety in a battery device as the risk of explosion is virtually eliminated in the former case. The battery concept, as of the preferred embodiment of the invention described above, embodies the safety aspect by considering only non-water sensitive and low toxicity materials for electrode fabrication and for the electrolytes as well. Carbon electrode surfaces are very reactive and  
10 especially so at high current rates, and require overcharge protection. Also nickel-cobalt oxides are prone to dangerous reactions as well. The manganese oxides are safe in all respects and no charge protection is necessary.

#### BRIEF DESCRIPTION OF THE DRAWINGS

15

The features and advantages of the invention are further set out in the following examples, given by way of non-limiting example with reference to the appended drawings in which:

FIG.1 shows a side view of an electrochemical generator of the invention with a  
20 partial sector showing the arrangement of the internal layers; (1,2) active material mesoporous electrode layers, (3) the porous separator layer, (4,5) the current collectors.

FIG.2 shows SEM images of the said mesoporous lithium manganate sintered layer under time and conditions set according to a preferred embodiment of the  
25 invention.

FIG.3 shows cyclic voltammograms of 1.5 micron layers of the said lithium manganate as a function of treatment temperature.

FIG.4 shows the comparison under shallow cycling of the various types of electrodes under identical potential scan and electrolyte conditions, in order to  
30 demonstrate the improved kinetics in the charge/discharge performance of said mesoporous lithium manganate material as a positive electrode.

FIG.5 shows the electrolyte function at steady-state current of the thin layer battery as perceived by the simulation model describing the electrolyte transport behavior of a completely mesoporous cell, by means of the concentration profiles of the  $\text{Li}^+$  and the coupling anion species within a multilayer design.

FIG.6 shows examples of electrolytes and their electrochemical properties used in the cell described above.

FIG.7 shows examples of several differently sized  $\text{TiO}_2/\text{Li}_y\text{Mn}_2\text{O}_4$  accumulators with respect to current and voltage discharge behavior. All cells utilize pure cellulose paper (30-40 microns) as the separator.

## DETAILED DESCRIPTION OF THE INVENTION

### EXAMPLE 1

According to a first embodiment, a secondary electrochemical generator of the "rocking chair" type has  $\text{TiO}_2/\text{Li}_y\text{Mn}_2\text{O}_4$  negative and positive electrodes respectively and of the cell configuration depicted in **Figure 1**. The mesoporous layers are deposited on conducting tin oxide coated glass sheets by the methods previously described. Devices display 20C (or C/0.05) discharge rates under short circuit. The above cell in  $30\text{ cm}^2$  form battery and a thin layer configuration comprising 10 micron mesoporous layers of the active materials, according to a preferred embodiment, with a separator of pure cellulose paper of 30-40 microns, utilizing electrolyte comprised of methoxypropionitrile and lithium bis-(trifluorosulfonyl) imide, is observed to sustain a 10C (or C/0.1) discharge rate and maintain a cell voltage of 1.5V, resulting in power densities above 1500 W/kg and energy densities above 210 Wh/kg.

### EXAMPLE 2

The porosity of a typical sintered layer of the nanosized oxide of an average 8 nm layer estimated by mass to surface measurements reaches as high as 30-70%. Very porous appear to be the layers in the case of 1.5 micron sintered films treated at 400 and 700 °C, the behavior of which is seen in **Figure 3**. The

two insertion levels for the spinel in the 4V range reported in the literature (W. Liu et al., J. Electrochem. Soc., Vol.143, No. 3, (1996), 879-884) for 200nm layers at 0.05mV/s, appear very distinct for our 1.5 micron thickness recorded at a sweep rate over two orders of magnitude higher, demonstrating the higher  
5 reversibility in the intercalation kinetics in comparison to the earlier materials, attainable by decreasing the particle size to the nanometer range and simultaneously ensuring effective particle connectivity and mesoporosity. The 700°C material appears to be less resistive and increased electrochemical reversibility and the capacity much higher as compared to the 400°C treatment  
10 due to the effective interconnectivity by sintering and material formation at the high temperature, as seen in Figure 2.

### EXAMPLE 3

Sintering the primary particles in order to obtain a bicontinuous porous network  
15 and thus a high connectivity should therefore be determinant to performance. The idea toward improving the manganates by imparting mesoscopic morphology to a continuous phase i.e. by retaining the connectivity as well as decreasing the primary particle to the nanometer range, significant improvements to the intercalation properties are expected. Making intimate  
20 electrical contact within the active mass regardless of size and shape of the oxide, results in enhanced utilization of the oxide and is therefore very desirable. For comparison electrodes are made from the commercial spinel  $\text{LiMn}_2\text{O}_4$  materials, namely the Selectipur and 5.2 micron particle powders, both supplied by Merk. The Selectipur particles consist of large hollow spheres  
25 (30 micron) the walls of which appear on SEM to have primary grains of 100-200 microns, extremely tight merged packing; the other appears as a fragmented form of the Selectipur. The pre-formed powders are made into electrodes by mixing the powder with PVA (MW 100000) as binder and graphite particles (Lonza KS-10 or carbon nanotubes) as the conducting matrix. The  
30 weight percentage of the constituents are chosen maximum 3% PVA and 10% graphite. The pastes are cast on CTO substrates ambient dried and then heated in an air furnace for 15min at 200 °C. As electrolyte a 1M  $\text{LiClO}_4$  in

propylene carbonate is the standard in all electrode cycling experiments to enable objective comparison. Depicted in **Figure 4** is the comparison between the Merck powders and a 8 micron mesoporous layer under shallow cycling of the various types of electrodes under identical potential scan and electrolyte

5 conditions, in order to demonstrate the improved kinetics in the discharge performance of said mesoporous lithium manganate material as a positive electrode. Cyclic voltammetric information elucidates the kinetic aspects of the lithium insertion/extraction in the oxides of the above thin film electrodes. The Selectipur and 5.2 micron particle electrodes display higher irreversibility than

10 the electrode from the mesoporous material treated at 700 °C. as evidenced by the higher induced polarization and discharge peak potential shift toward more negative in the case of the commercial materials. The mesoporous layer shows a clear advantage over the even higher capacity (larger active mass) Selectipur electrode that contains conducting carbon.

15

#### EXAMPLE 4

The preferential kinetics are also exemplified by the comparison of the Selectipur 30-40µm electrode the 8µm mesoporous layer. In the same voltammetric set up and under a potential scan of 100mV/s a 1.75 to 2 mA/cm<sup>2</sup>

20 delithiation current at 1.5V vs. AgCl and 7.5 mA/cm<sup>2</sup>, in both cases respectively. At 20mV/s a 1.25 mA/cm<sup>2</sup> current was measured in the first case and 5 mA/cm<sup>2</sup> in the second. As another example a 3 micron LiMn<sub>2</sub>O<sub>4</sub> electrode in PC, 1M Li<sup>+</sup>, at short circuit gave a 1.4 mA/cm<sup>2</sup>/micron on charge and discharge. The corresponding value for the delithiation of TiO<sub>2</sub> was 0.4

25 mA/cm<sup>2</sup>/micron. The above Selectipur 30-40µm electrode gave 0.055 mA/cm<sup>2</sup>/micron.

Cyclability was the normally expected for the temperature treatment applied and described in the literature. In the glove box, 10% capacity loss was observed within the first 50 cycles at 5 mV/s scan rate and between 1.4 - 2.8V

30 as voltage limits.

#### EXAMPLE 5

Thin layer cell ionic transport conditions at steady-state are modeled for the mesoporous electrode intercalation cell. The cell configuration consists of two 1 millimeter lithium intercalation mesoporous hosts separated by a 20 micron inert and insulating (meso-)porous spacer, one of the active material layers acting as the insertion and the other as the de-insertion (lithium extraction) electrode. The initial electrolyte concentration in monovalent lithium salt is 1M and the free stream diffusion coefficient for  $\text{Li}^+$  in the electrolyte corresponds to the case of propylene carbonate ( $3 \cdot 10^{-6} \text{ cm}^2/\text{s}$ ) of approximately 3 cP.

In the depicted results of the model the concentration profile of the  $\text{Li}^+$  (also the overlapping curve for the anion) appears in **Figure 5a** and the potential drop across the cell in **Figure 5b** when approx.  $6 \text{ mA}/\text{cm}^2$  are passing through the cell, the minimum current limiting the supply of  $\text{Li}^+$  to one side of the intercalating electrode. The conductivity of the host solid is not considered here. The electrode porosities are 50% and 90% for the separator layer.

Anything smaller than 1000 micron (1mm) would increase the limiting currents. It is noted that the absence of supporting electrolyte in this case aids the lithium ion diffusion or transport but at a cost of potential in the form of IR drop across the cell (here just under 0.2 V, as depicted in the **Figure 5b**. This calculation reveals that for electrodes of 10 microns in the above configuration, currents as high as  $500 \text{ mA}/\text{cm}^2$  are possible as far as electrolyte performance is concerned.

In addition, the  $\text{TiO}_2$ /cellulose paper/ $\text{LiMn}_2\text{O}_4$  cells, with active mesoporous layers of about 10 microns, could deliver more than  $5 \text{ mA}/\text{cm}^2$  at short circuit, with molten salts containing 1-2 M lithium - bis (trifluorosulfonyl) imide that has a much higher viscosity ( $>40 \text{ cP}$ ) than in the propylene carbonate case, and thus a lower  $\text{Li}^+$  diffusion coefficient.

#### EXAMPLE 6

From the viewpoint of electrolyte investigation and characterization the sought for properties are generally low viscosity, low volatility, solubility of the lithium salt electrolytes and electrochemical stability/chemical compatibility with the

electrode materials. Synthesized are room temperature ionic liquids which have very attractive features in the above respects. The electrochemical stability limits fulfill the requirements for 4V cathode materials, as seen from the examples shown in **Figure 6a**. The potentials are expressed versus iodide/tri-iodide which is +0.15V vs. AgCl. Di-methyl-ethyl-imidazolium imide offers the best cathodic stability advantages.

Solubility of more than 2M lithium-bis (trifluorosulfonyl) imide can be reached in methoxy-diethoxy propionitrile and in methoxypropionitrile. The electrochemical stability of this newly synthesized organic solvent as evidenced by the electrochemical window is given in **Figure 6b**. The corresponding stability range for methoxypropionitrile is depicted by the bar in this figure, and the operation limits of the lithium hosts  $\text{TiO}_2$  and lithium manganate are positioned against this scale (ferrocene potential is +0.4V vs. AgCl) in **Figure 6c**.

These molecular structures are designed to exploit the strong solvating properties of the ether groups toward  $\text{Li}^+$ , combined with the low viscosity for  $\text{Li}^+$  diffusion and the relatively high boiling points of these compounds to decrease their volatility. Methoxy-ethoxy-propionitrile is also synthesized having viscosity 2.7cP, 1.1cP being for methoxypropionitrile and 5cP for methoxy-diethoxy propionitrile. The boiling points are respectively 240C, 165°C and at 10mmHg 152°C.

#### EXAMPLE 7

According to a second embodiment, a secondary electrochemical generator of the "rocking chair" type has  $\text{TiO}_2/\text{Li}_y\text{Mn}_2\text{O}_4$  negative and positive electrodes respectively as described in EXAMPLE 1 and of the cell configuration depicted in **Figure 1**, however, with the separator layer (3) consisting of a mesoporous zirconia layer of 8 micron thickness and 60% porous, prepared as described by P.Bonhote et al., J.Phys.Chem.B. (1998), 102, 1498-1507, displays performance characteristics matching those disclosed in EXAMPLE 1. This mesoporous separator offers advantages for electrolyte penetration in the phase of electrolyte filling of the said electrochemical generator and effective retention of the electrolyte within the mesopores and thus within the generator as a whole,

combined with effective displacement of gas from the space of the said generator on electrolyte filling, as well as during operation, that is the effective accommodation of volumetric changes on charge/discharge cycling, allowing for electrolyte movement and gas expulsion from the generator layers(1,2,3) by  
5 forced capillary filling of the pores by the liquid electrolyte.



## CLAIMS

What we claim is:

1. A high capacity and high power density primary or secondary  
5 electrochemical generator having two electrodes supporting different electroactive materials, said electrodes being connected together by an electrolyte, characterized in that the electroactive material used in the composition of at least one electrode includes an oxide or chalcogenide of transition metals or their lithiated or partially lithiated forms selected  
10 from  $\text{TiO}_2$ ,  $\text{Nb}_2\text{O}_5$ ,  $\text{WO}_3$ ,  $\text{V}_2\text{O}_5$ ,  $\text{MoO}_3$ ,  $\text{MnO}_2$ ,  $\text{Li}_x\text{Mn}_2\text{O}_4$ ,  $\text{HfO}_2$ ,  $\text{TiS}_2$ ,  $\text{WS}_2$ ,  $\text{TiSe}_2$ ,  $\text{Li}_x\text{NiO}_2$ ,  $\text{Li}_x\text{CoO}_2$ ,  $\text{Li}_x(\text{NiCo})\text{O}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{Fe}_3\text{O}_4$ ,  $\text{RuO}_x$ ,  $\text{Fe}_x\text{S}_2$ ,  $\text{Ru}_x\text{S}_2$ ,  $\text{MoS}_2$ ,  $\text{WS}_2$ ,  $\text{Ir}_x\text{O}_2$ ,  $\text{Ce}_x\text{O}_2$ ,  $\text{Li}_x\text{Na}_y\text{MnO}_z\text{I}_n$  ( $n < 1$ ),  $\text{In}_x\text{O}_3$ ,  $\text{Ta}_x\text{O}_5$ ,  $\text{SnM}_x\text{O}_y$ , where M is one of glass forming metallic elements or a mixture of these elements, or  $\text{Sn}_x\text{O}_2$  in mesoporous form having a pore  
15 size of 0.001 to 10 micron and a specific surface area between 2 and 2000  $\text{m}^2/\text{g}$ .
2. An electrochemical generator according to claim 1 characterized in that  
20 the mesoporous electrode is characterized by a three dimensional bicontinuous structure consisting of an interconnected solid phase material used for reversible ion intercalation and for electronic transport which is in contact with an interconnected porous space filled with electrolyte the latter serving for ionic transport, said electrode being characterized by a morphology of the solid phase that is designed to  
25 overcome impediment of ionic diffusion in the electrolyte encountered with conventional high surface area electrodes and a three dimensional structure ascertaining interconnectivity, mechanical stability of the solid phase as well as access of the electrolyte to the entire pore space.
- 30 3. An electrochemical generator according to claim 1 or 2 characterized in that the mesoporous electrically active material is prepared by precipitating a precursor compound of said material in aqueous solution via a sol-gel method followed by deposition of the precursor on a

conductive support and sintering at a temperature between 300 and 800 °C.

4. An electrochemical generator according to any of claims 1 to 3  
5 characterized in that the mesoporous electrically active material is prepared by chemical reaction between precursor compounds in aqueous solution in the presence of surfactant micelles, the said surfactant micelles acting as templates to produce the desired mesoporous morphology, particularly in the form of ordered hexagonal  
10 arrays.
5. An electrochemical generator according to any of claims 1 to 4  
characterized in that the electrically active material is composed of elongated interconnected members, that are connected to other  
15 elongated members in at least two points of an aspect ratio of at least 4 and of which the small dimension of the member is smaller than 300 nm.
6. An electrochemical generator according to any of claims 1 to 5  
characterized in that the electrically active material is prepared by  
20 inclusion of solvents to the particle or precursor in order to exert control over the texture and the morphology of the said material and of the porosity of the electrode, which can be controlled from 70% to 25% by changing the ratio of oxide precursor grains versus solvent.
- 25 7. An electrochemical generator according to any of claims 1 to 6 characterized in that the mesoporous electrically active material is comprised of mesoporous 5-20 micron beads or rods which are electrically connected together by compressing in the form of pellets of films a mixture composed of said beads or rods, of carbon powder or  
30 conducting polymer or other matrix and of a bonding material contained in solvent, then drying said mixture on a conducting support and/or baking at temperature and long enough time for binder or conductive matrix conversion to desired state.

8. An electrochemical generator according to any of claims 1 to 8 characterized in that the electrolyte contains alkali or alkaline earth metals in cationic form.
- 5 9. An electrochemical generator according to any of claims 1 to 5 or 7 to 8 and claim 6 characterized in that the alkali metal is lithium on the form of one of its salts chosen from tetrafluoroborate, hexafluorophosphate, hexafluoroantimonate, hexafluoroarsenate, trifluoromethane sulfonate, bis-(trifluorosulfonyl) imide, tris-(trifluorosulfonyl)methide, trifluoro-  
10 methanesulfonate, trifluoroacetate, tetrachloroaluminate or perfluorobutane sulfonate.
10. An electrochemical generator according to any of claims 1 to 9, characterized in that the electrolyte includes and aprotic solvent selected  
15 from ethylene carbonate, propylene carbonate, dimethylcarbonate, diethylcarbonate, dioxolane, butyrolactone, methoxypropionitrile, methoxy-ethoxy propionitrile, methoxy-diethoxypropionitrile, methoxyacetonitrile, tetrafluoro-propanol or mixtures of these solvents.
- 20 11. An electrochemical generator according to any of claims 1 to 10 characterized in that the electrolyte includes a molten salt as a solvent for the lithium ion containing salt, such as methyl-ethyl-imidazolium trifluoromethanesulfonate, methyl-ethyl-imidazolium bis (trifluorosulfonyl) imide or alkylguanidinium bis (trifluorosulfonyl) imide.  
25
12. An electrochemical generator according to any of claims 1 to 11, characterized in that the electrically active material of one electrode or of each of the two electrodes, is capable of forming an intercalation compound with the alkali or alkaline earth metal.
- 30 13. An electrochemical generator according to any of claims 1 to 12, characterized in that the electrically active material of one electrode is composed of  $\text{TiO}_2$  in anatase form having a mesoporous structure.

14. An electrochemical generator according to any of claims 1 to 13,  
characterized in that the negative electrode includes mesoporous  $\text{TiO}_2$   
and the composition of the positive electrode includes  $\text{Li}_y\text{Mn}_2\text{O}_4$  ( $y < 2$ )  
5 in amorphous or crystalline form, the electrolyte being composed of a 1M  
solution of lithium bis-(trifluorosulfonyl) imide in methoxypropionitrile as a  
solvent.
15. An electrochemical generator according to any of claims 1 to 14,  
10 characterized in that the mesoporous electrically active material  
comprised of mesoporous 5-20 micron beads or rods form an electrode  
by templated ordering, manipulative stacking or arrangement of the said  
5-20 micron secondary mesoporous particles in a manner that controls  
particle orientation, the secondary porosity and the said particle electrical  
15 contact by means of an additive conducting matrix or by treatment  
(chemical, temperature, external energy field such as ultrasonic,  
electromagnetic) of the conducting additive or its precursor or of the  
template itself in order to form the conductive phase.
- 20 16. An electrochemical generator according to any of claims 1 to 12 or 14 to  
15, and claim 13, characterized in that separator (3) is a porous or  
mesoporous, high porosity insulating material such as ceramic (zirconia,  
alumina) or glass or polypropylene, the above in the forms of continuous  
layers or particle spacers and the current collector-substrate (4,5) is  
25 taken from options such as carbon, graphite paper, stainless steel,  
titanium or aluminium alloy, DSA, or consist of the conductive matrix  
incorporated for conductivity enhancement. Also, characterized in that a  
distributed within the active mass or dendritic conductive collector of the  
above is used.

Fig. 1

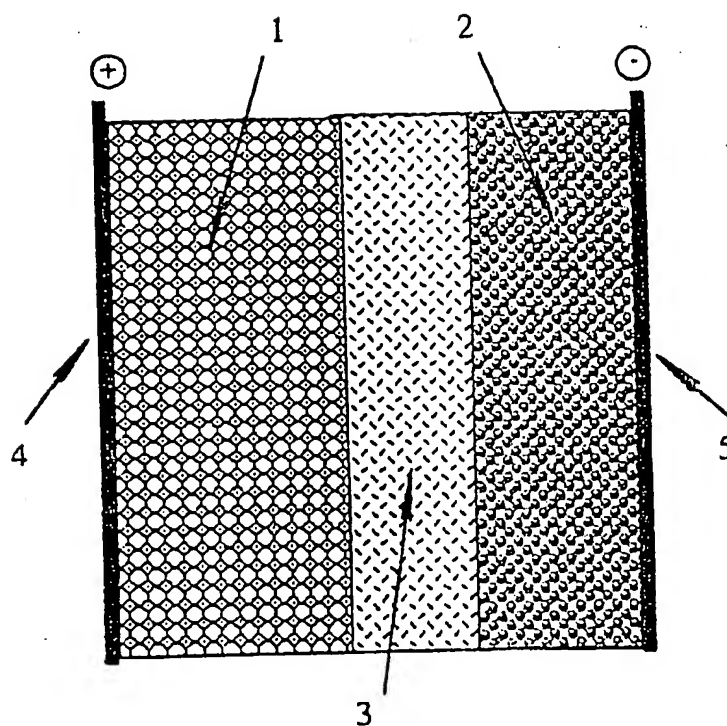


Fig. 2

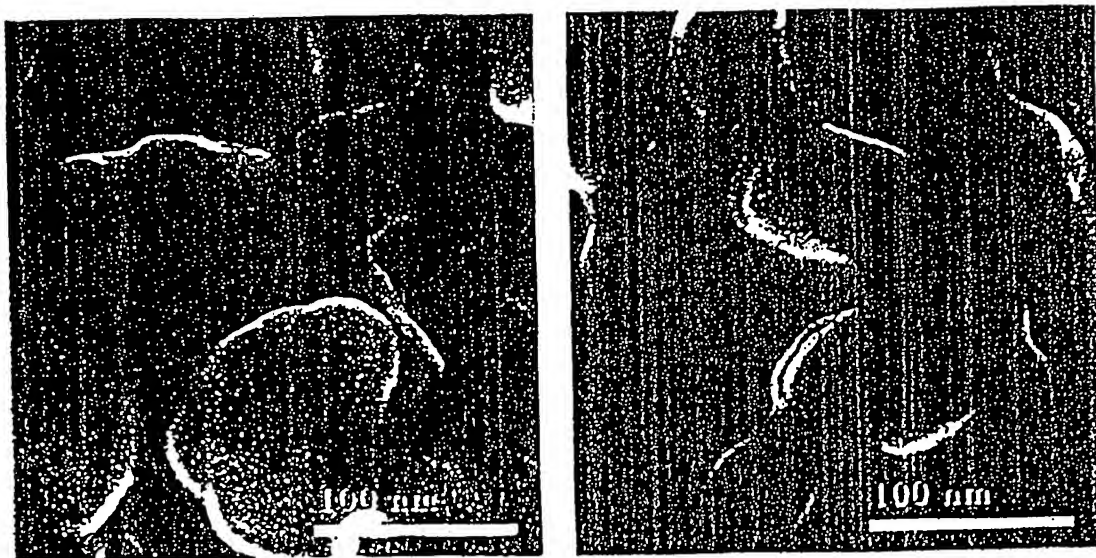


Fig. 3

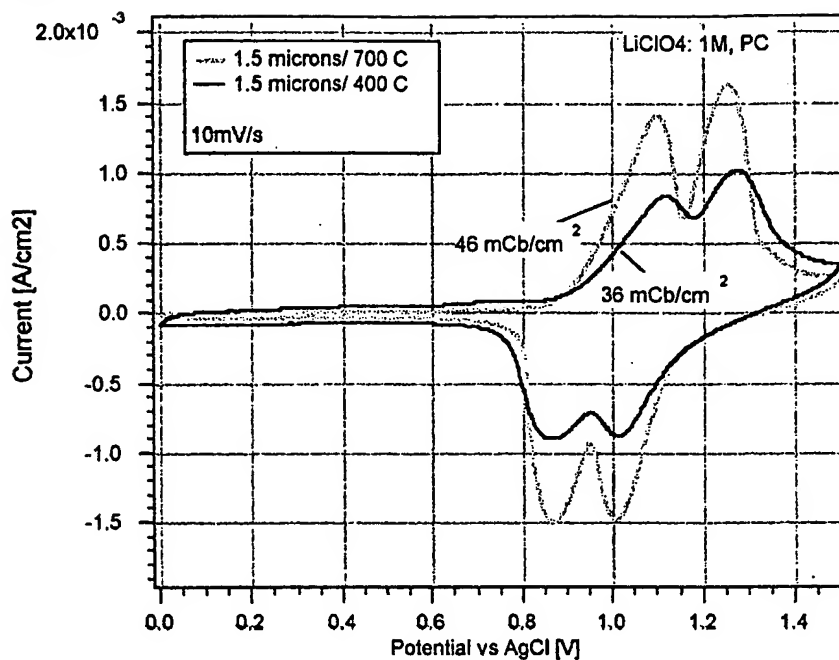


Fig. 4

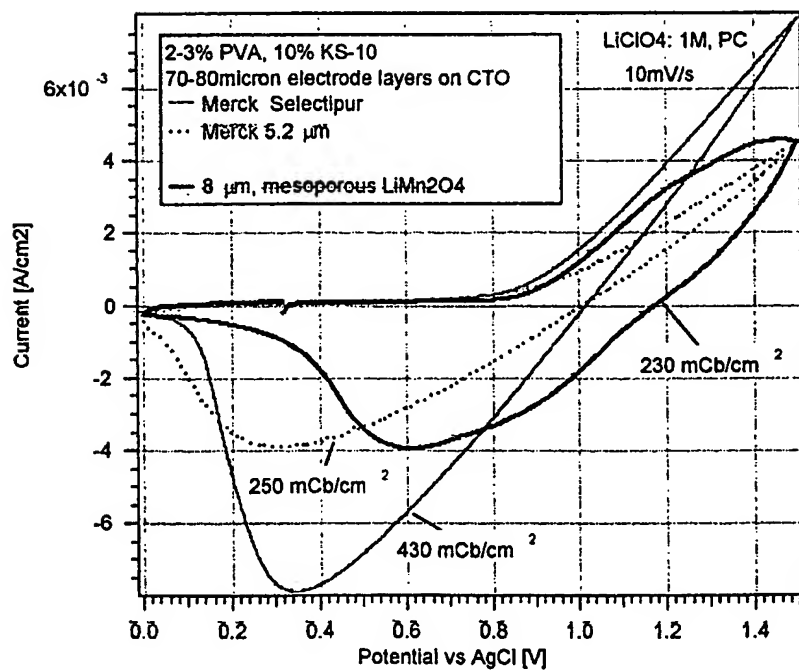


Fig. 5a

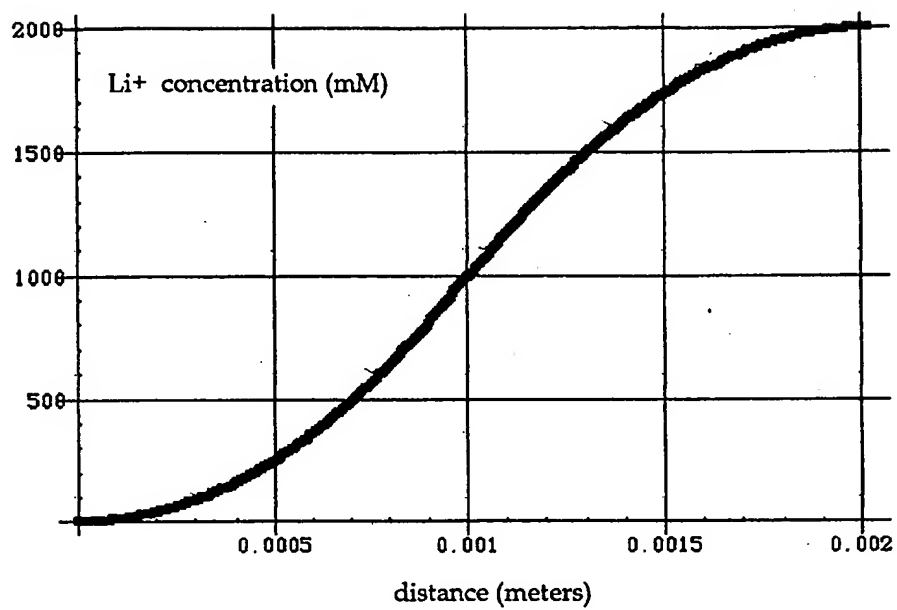


Fig. 5b

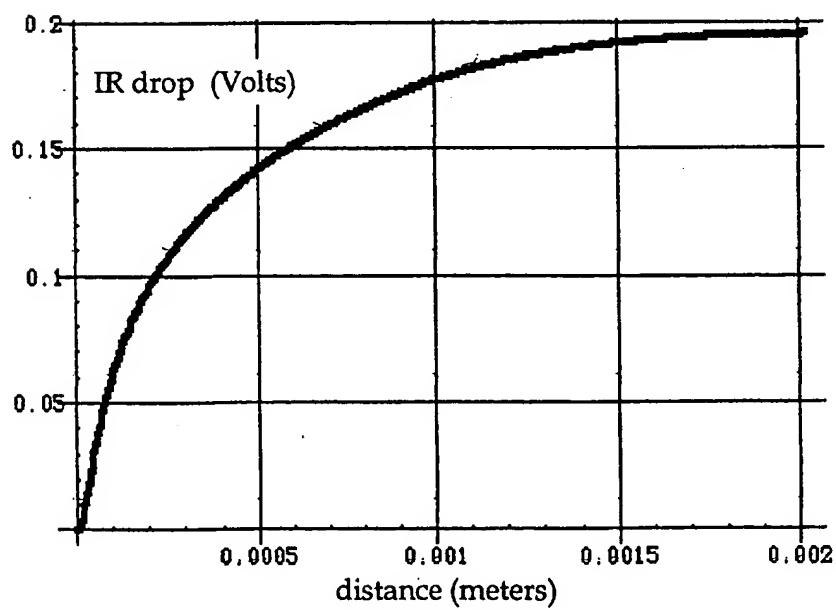


Fig. 6a

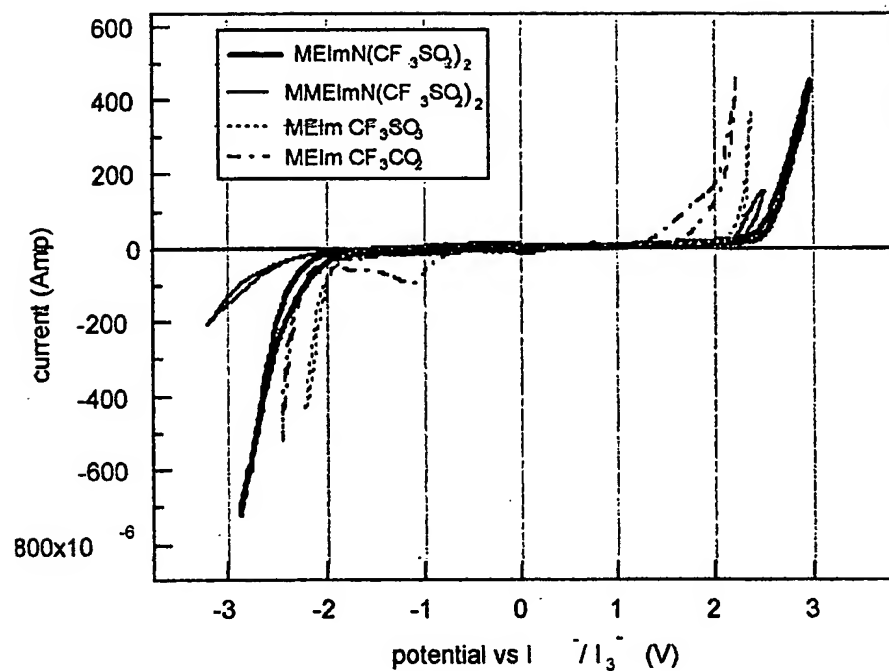


Fig. 6b

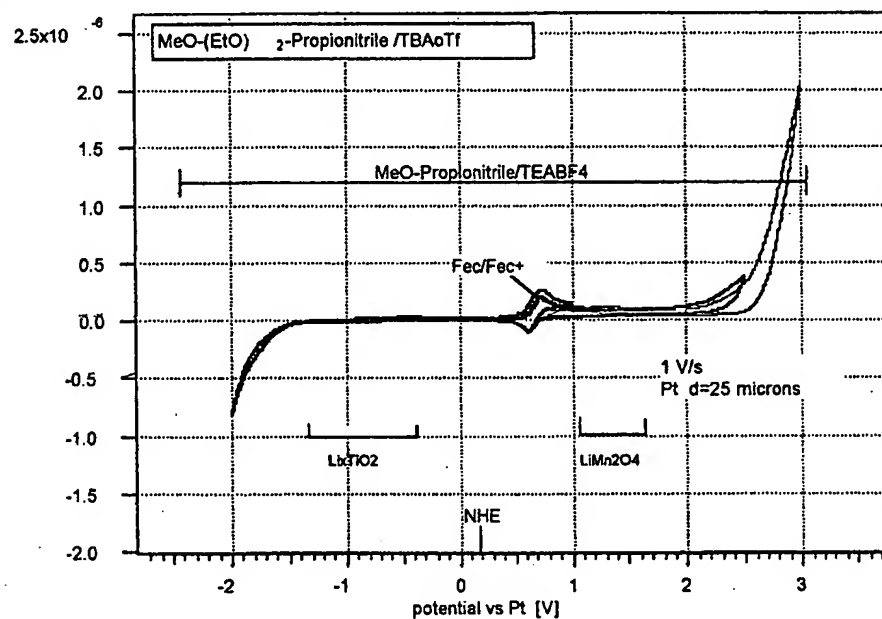




Fig. 6c

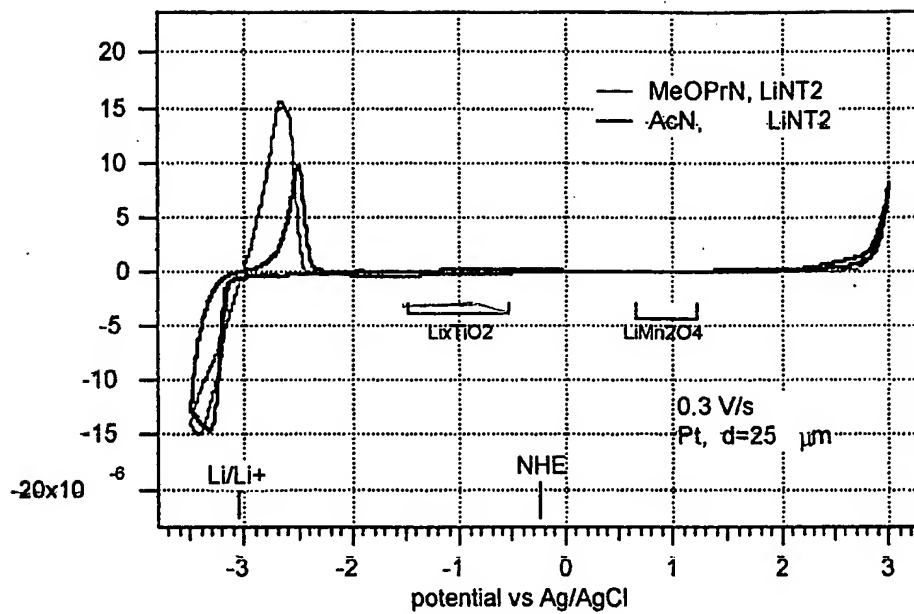


Fig.7 a

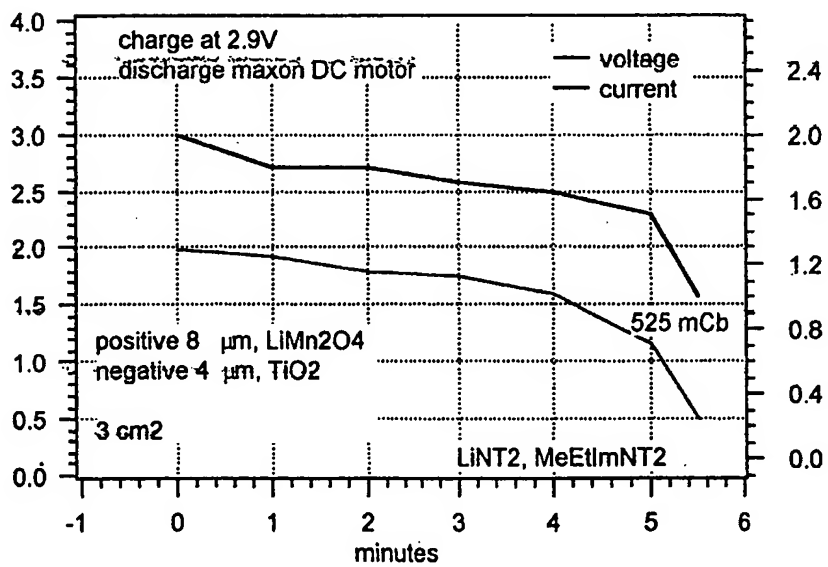
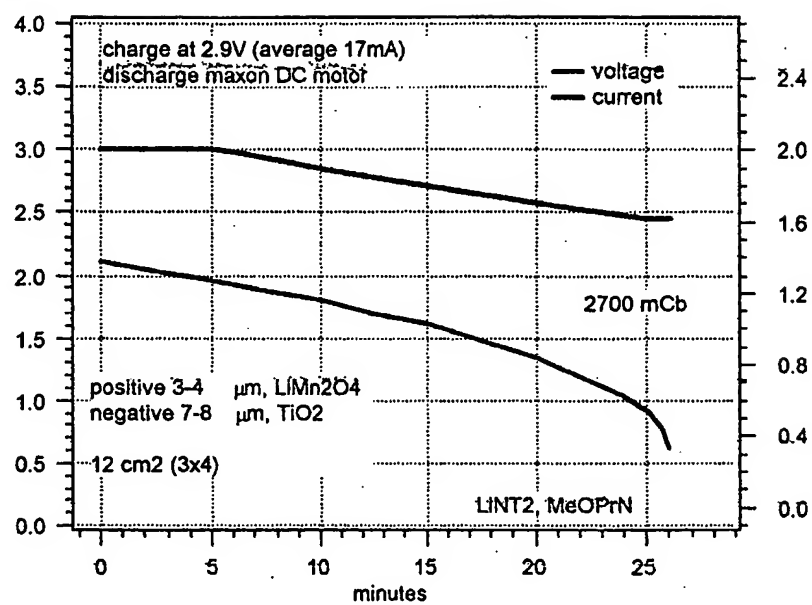


Fig.7b



# INTERNATIONAL SEARCH REPORT

International Application No

PC./EP 99/03261

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 6 H01M10/40 H01M4/48 H01M4/58

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 H01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 558 680 A (TAKEUCHI ESTHER S ET AL) 24 September 1996 (1996-09-24) claims 1-21	1-10
A	WO 98 04010 A (FUJITA YUKO ;AMINE KHALIL (JP); YASUDA HIDEO (JP); JAPAN STORAGE B) 29 January 1998 (1998-01-29) claims 1-14	1-10
A	US 5 426 006 A (DELNICK FRANK M ET AL) 20 June 1995 (1995-06-20) claims 1-35	1-10
	--- -/--	



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

### \* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search

20 September 1999

Date of mailing of the international search report

27/09/1999

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl.  
Fax: (+31-70) 340-3016

Authorized officer

Battistig, M

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/E 99/03261

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>PATENT ABSTRACTS OF JAPAN  vol. 013, no. 374 (E-808),  18 August 1989 (1989-08-18)  &amp; JP 01 128354 A (NIPPON TELEGR &amp; TELEPH  CORP ;OTHERS: 01),  22 May 1989 (1989-05-22)  abstract</p> <p>-----</p>	1-10

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/Er 99/03261

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5558680 A	24-09-1996	NONE	
WO 9804010 A	29-01-1998	EP 0914683 A	12-05-1999
US 5426006 A	20-06-1995	NONE	
JP 01128354 A	22-05-1989	NONE	

**This Page is Inserted by IFW Indexing and Scanning  
Operations and is not part of the Official Record**

**BEST AVAILABLE IMAGES**

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☒ BLACK BORDERS
- ☐ IMAGE CUT OFF AT TOP, BOTTOM OR SIDES
- ☐ FADED TEXT OR DRAWING
- ☐ BLURRED OR ILLEGIBLE TEXT OR DRAWING
- ☐ SKEWED/SLANTED IMAGES
- ☒ COLOR OR BLACK AND WHITE PHOTOGRAPHS
- ☐ GRAY SCALE DOCUMENTS
- ☐ LINES OR MARKS ON ORIGINAL DOCUMENT
- ☐ REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY
- ☐ OTHER: \_\_\_\_\_

**IMAGES ARE BEST AVAILABLE COPY.**

**As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.**